SDAC-TR-75-15

12

HIDE-IN-EARTHQUAKE COUNTERMEASURES USING EARTHQUAKE P SHADOW ZONE AND EXPLOSION PKP CAUSTIC ZONE

R.R. BLANDFORD, E.I. SWEETSER, and T.J. COHEN
Seismic Data Analysis Center
Teledyne Geotech, 314 Montgomery Street, Alexandria, Virginia 22314

25 SEPTEMBER 1975

Sponsored By
The Defense Advanced Research Projects Agency
Nuclear Monitoring Research Office
1400 Wilson Boulevard, Arlington, Virginia 22209
ARPA Order No. 1620

Monitored By
VELA Seismological Center
312 Montgomery Street, Alexandria, Virginia 22314

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: 14 SDAC-TR-75-15	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): 6 HIDE-IN-EARTHQUAKE COUNTERMEASURES USING EARTHQUAKE P SHADOW ZONE AND EXPLOSION PKP CAUSTIC ZONE.		5. TYPE OF REPORT & PERIOD COVERED: 9 Technical rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Blandford, R. R., Sweetser, E. I., and Cohen, T. J.		8. CONTRACT OR GRANT NUMBER(s): 15 F08606-76-C-0004, ARPA Order-1620
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Teledyne Geotech, 314 Montgomery Street, Alexandria, Virginia 22314		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 16 VT/6709
11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Advanced Research Projects Agency, Nuclear Monitoring Research Office, 1400 Wilson Blvd.-Arlington, Virginia 22209		12. REPORT DATE: 11 25 Sep~~tember~~ 1975
		13. NUMBER OF PAGES: 28
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): VELA Seismological Center, 312 Montgomery Street, Alexandria, Virginia 22314 — 12 31p.		15. SECURITY CLASS. (of this report): Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

10 R. R. /Blandford, E. I. /Sweetser
T. J. /Cohen

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Evasion	Hide-in-Earthquake
Counterevasion	HIE
PKP	
Core Shadow	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Established distance-amplitude curves are used to illustrate the feasibility of a method to detect the presence of a seismic phase from an underground explosion in the coda of an earthquake. The advantage of the technique arises from the fact that the amplitude of an earthquake coda is reduced on recordings taken in the core shadow zone while the amplitude of PKP from an explosion is enhanced in its caustic zone. (cont on p 1473 B)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified 408 258

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

LB

(cont fr p 1473A)

Results of the study indicate that the method can be effective even if the explosion and earthquake are located only two to five degrees apart.

ACCESSION for		
NTIS	White Section	☑
DDC	Buff Section	☐
UNANNOUNCED		☐
JUSTIFICATION		
BY		
DISTRIBUTION/AVAILABILITY CODES		
Dist.	AVAIL. and/or SPECIAL	
A		

HIDE-IN-EARTHQUAKE COUNTERMEASURES USING EARTHQUAKE P SHADOW ZONE AND EXPLOSION PKP CAUSTIC ZONE

SEISMIC DATA ANALYSIS CENTER REPORT NO.: SDAC-TR-75-15

AFTAC Project Authorization No.: VELA T/6709/B/ETR

Project Title: Seismic Data Analysis Center

ARPA Order No.: 2551

ARPA Program Code No.: 6F10

Name of Contractor: TELEDYNE GEOTECH

Contract No.: F08606-76-C-0004

Date of Contract: 01 July 1975

Amount of Contract: $2,319,926

Contract Expiration Date: 30 June 1976

Project Manager: Royal A. Hartenberger
(703) 836-3882

P. O. Box 334, Alexandria, Virginia 22314

ABSTRACT

Established distance-amplitude curves are used to illustrate the feasibility of a method to detect the presence of a seismic phase from an underground explosion in the coda of an earthquake. The advantage of the technique arises from the fact that the amplitude of an earthquake coda is reduced on recordings taken in the core shadow zone while the amplitude of PKP from an explosion is enhanced in its caustic zone.

Results of the study indicate that the method can be effective even if the explosion and earthquake are located only two to five degrees apart.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

INTRODUCTION

A number of studies (e.g. Filson (1973), Jeppsson (1975), Evernden (1976)) have been made of the hide-in-earthquake (HIE) evasion technique in which the evader waits for a large earthquake and then detonates his test, relying on the seismic noise from the earthquake to conceal the signal from the explosion. The subject has also been briefly discussed by Lukasik (1971).

Jeppsson (1975) and other workers have suggested that a useful counter-evasion technique would be to look for evidence of the explosions at stations in the core shadow of the earthquake. To identify better the core shadow zone, Sweetser and Blandford (1973) investigated the amplitude-distance relations for PP, P_{diff}, and PKP (Figure 1). This work also emphasized the large amplitudes at the PKP caustic and suggested that a related counterevasion technique would be to look at data from stations near the PKP caustic of suspected test sites.

Filson, J. R., 1973, On estimating the effect of Asian earthquake codas on the explosion detection capability of LASA, Technical Report 1973-29, Lincoln Laboratory, Massachusetts Institute of Technology.

Jeppsson, Ingvar, 1975, Evasion by hiding in earthquakes, FOA Rapport C 20042-T1, Forsvarets Forskningsanstalt, Stockholm, Sweden.

Evernden, J., 1976, Study of seismological evasion, Part I, general discussion of various evasion schemes, Bull. Seis. Soc. Am., v. 66, p. 245-280.

Lukasik, S., 1971, In Hearings on Status of current technology to identify seismic events as natural or man-made, before the Joint Committee on Atomic Energy of the Congress of the United States, October 1971. GPO No. 69-648.

Sweetser, E. I. and R. R. Blandford, 1973, Seismic distance-amplitude relations for short-period P, P_{diff}, PP and compressional core phases for $\Delta > 90°$. SDAC-TR-73-9, Teledyne Geotech, Alexandria, Virginia.

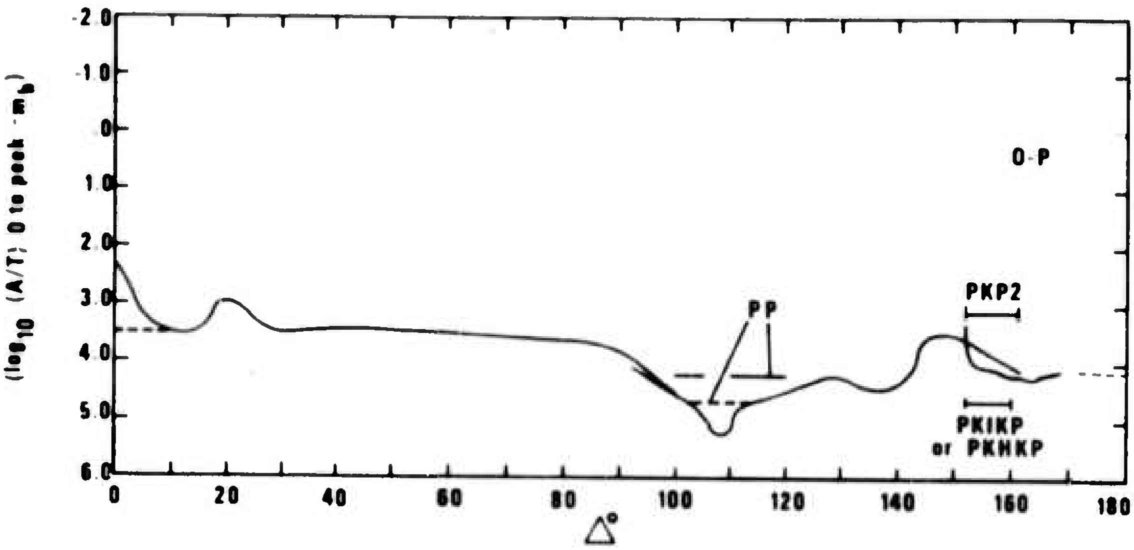


Figure 1. Distance-amplitude relations for zero-to-peak $\log_{10}(A/T)$ amplitudes of P, P_{diff}, and PKP from Veith and Clawson (1972) for 40 km depth from Sweetser and Blandford (1973).

While the number which most completely characterizes the detectability of the explosion in the earthquake is the difference in the B-factors from the epicenters to the stations, a full study of the problem requires the availability of typical earthquake coda shapes for several distance ranges together with estimates of coda characteristics which are unique to the various epicentral regions and detecting stations. Catalogs of coda shapes and discussions of some of these issues are given in papers by Cohen et al. (1972), Sweetser et al. (1973), Cohen and Sweetser (1973), Sweetser and Cohen (1973), Sweetser and Cohen (1974), and Blandford and Sweetser (1975). In

---

Cohen, T. J., E. I. Sweetser, and T. J. Dutterer, 1972, P and PKP coda decay characteristics for earthquakes, Seismic Data Laboratory Report No. 301, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I., T. J. Cohen, and M. F. Tillman, 1973, Average P and PKP codas for earthquakes, Seismic Data Laboratory Report No. 305, Teledyne Geotech, Alexandria, Virginia.

Cohen, T. J. and E. I. Sweetser, 1973, False alarm probabilities for mixed events, SDAC-TR-73-8, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I., and T. J. Cohen, 1973, Average P and PKP codas for earthquakes (103°-118°), SDAC-TR-73-10, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1974, Average P and PKP codas for earthquakes (118°-180°), SDAC-TR-74-19, Teledyne Geotech, Alexandria, Virginia.

Blandford, R. R. and E. I. Sweetser, 1975, Short-period earthquake coda shape as a function of geology and system response, SDAC-TR-75-10, Teledyne Geotech, Alexandria, Virginia.

this study we concentrate on the difference in B factors, which should in most cases provide an accurate indication of the stations which would be most fruitful to examine for evidence of hidden events from known test sites. Restricting the examination to only a few stations will lower the false alarm rate for fixed probability of detection of mixed events (see Cohen and Sweetser (1973) and Filson (1973)).

Stations which are selected for examination should exhibit good signal-to-noise ratios so that they may be used for the calculation of short-period discriminants. For a recent discussion of short-period discriminants, see Shumway and Blandford (1974).

Shumway, R. and R. R. Blandford, 1974, An examination of some new and classical short-period discriminants, SDAC-TR-74-10, Teledyne Geotech, Alexandria, Virginia.

RESULTS

The amplitude-distance relation outlined in Figure 1 has been contoured on the globe for an event located in Kamchatka at 52°N, 172.5°E (Figure 2). Figure 3 is the base map including station names and national boundaries to aid in analysis. If a very large earthquake occurred on Kamchatka, one might feel the need to examine the possibility of a test having been performed at any test site in the world. For such an occurrence, a useful first step in

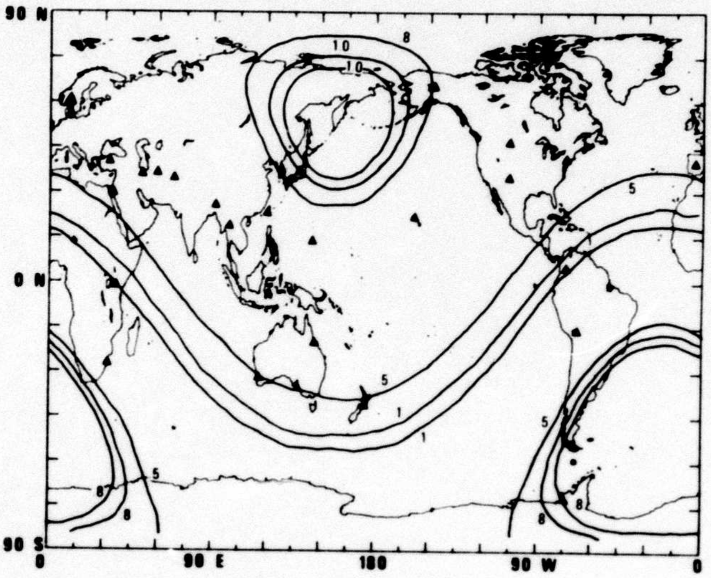


Figure 2. Log_{10} of the short-period signal amplitude minus the $\log_{10}$ of the minimum amplitude, for an earthquake at 52°N, 157.5°E, the tip of the Kamchatka Peninsula. The appropriate distance-amplitude relation is that given in Figure 1 by the dashed lines for $\Delta < 10°$ and $\Delta > 170°$, and by the solid line between 10° and 170° (the upper solid line for $152° < \Delta < 160°$). The contour lines of 0.1, 0.5, 0.8, and 1.0 were selected to best display the nature of the field without confusing the presentation. There are no values in the field ≤ 0.0 or ≥ 1.1.

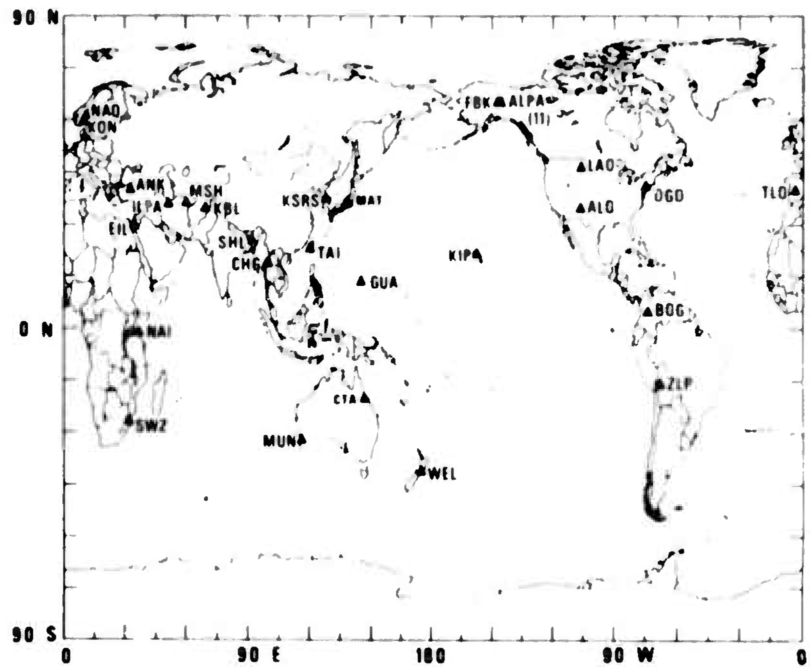


Figure 3. Map of proposed SRO stations plus LASA, ALPA, NORSAR, ILPA, KSRS.

the analysis would be to examine records from stations in the core shadow zone of the earthquake. We see that stations NAI in Africa, and BOG in Columbia lie in the earthquake core shadow zone, and so, the records for these stations should be examined for evidence of a test event. It should be noted, however, that even a small shift in the earthquake epicenter would greatly reduce the utility of these stations. As such, one would probably also want to examine one or more of the WWSSN stations illustrated in Figure 4. We shall see in this report that a large number of well distributed, but not necessarily sensitive, stations are required to make the most productive use of this counterevasion technique.

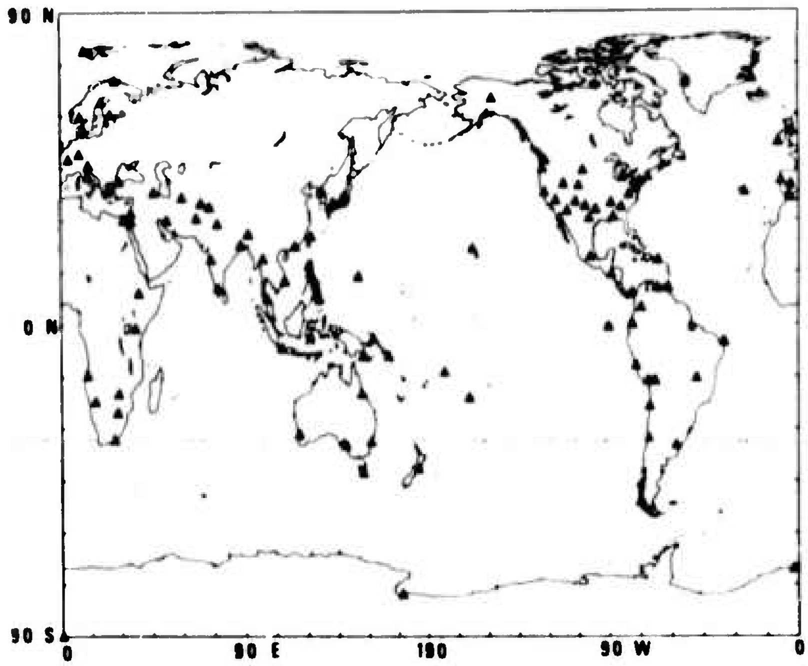


Figure 4. Map of WWSSN station locations reporting in 1972. Several others were reporting from Antarctica in 1967.

If there were a large earthquake elsewhere in the world, and one suspected that a test might be attempted on the Kamchatka Peninsula, one would also want to examine stations near the PKP caustic of the test site. In the lower right hand corner of Figure 2 we see that this region sweeps across Southern Brazil, Argentina, Chile, into Antarctica, and just brushes the Southern tip of Africa. There is no VELA network station anywhere in the caustic. However, there are two WWSSN stations in South America, and one in Africa, which are good possibilities. The three stations in Antarctica just miss the zone of expected large-amplitude arrivals. We shall see in this report that this is a common occurrence. If records were available from all the operational stations in Antarctica, they would make a valuable contribution to a counter-HIE network because of their strategic location with respect to the caustic from plausible

test sites in the Northern Hempisphere. Isherwood (1970) has also made the point that Antarctica is strategically located to detect test-site PKP, and presents a useful PKP record section and illuminating commentary.

In a practical situation one would know precisely the location of the earthquake and would often have a good idea as to possible explosion test sites. In this case the difference in the B-factors at each location on the earth is the important quantity. This immediately suggests that the derivative of the amplitude-distance curve is the important parameter in the case where the explosion and earthquake are close to one another.

In Figure 5 we have contoured the positive differential logarithms of amplitudes received from an explosion located in Kamchatka at 52°N, 157.5°E, and an equal magnitude earthquake located at 56°N, 163°E, at the northern

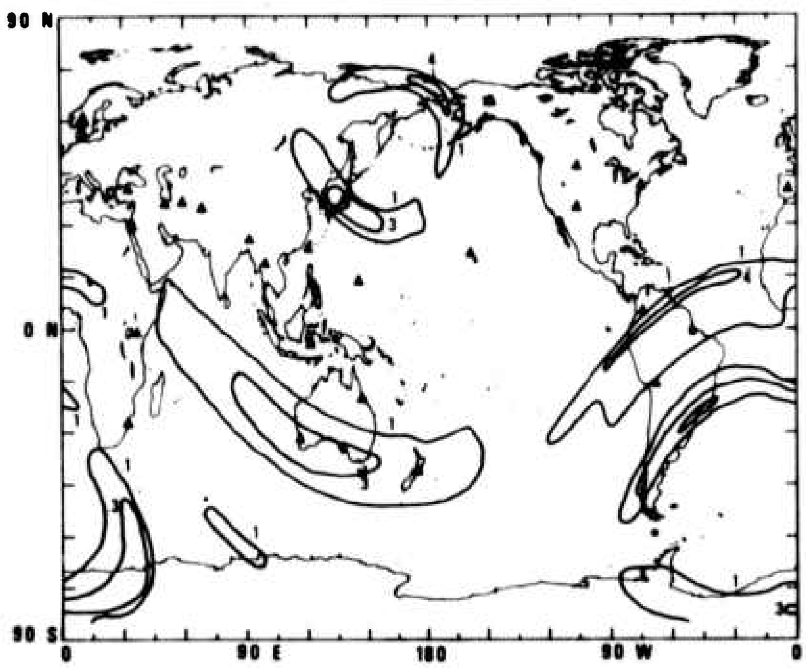


Figure 5. Positive differential logarithms of amplitudes expected to be received from a hypothetical explosion located in Kamchatka 52°N, 157.5°E and an equal magnitude earthquake located at 56°N, 163°E. Positive numbers indicate that the explosion signal is larger than the earthquake signal. Distance-amplitude relations are as described in Figure 2.

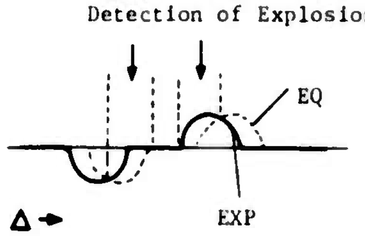
Isherwood, W. F., 1970, Investigation of PKP seismic waves, Project PHV6495 Stanford Research Institute, Menlo Park, California.

edge of Kamchatka seismicity. Positive differences indicate that the explosion's signal was larger than the earthquake's. Negative differences have not been contoured, since they are of little interest.

Comparison with Figure 2 shows that the regions of optimum detection which can be traced to the influence of the earthquake core-shadow zone have been shifted on the order of 10 degrees from the location of the minimum earthquake amplitude. The gaps in the detection contours occur at those azimuths from the epicenters perpendicular to the line between them. Along these paths the distances to the two events are equal, and there is little difference in the amplitudes received.

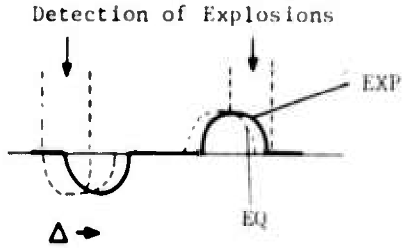
Notice in Figure 5 that for Eastern latitudes, the maximum shadow zone detectability occurs closer to the test events than does the minimum of the earthquake amplitude level in Figure 2, while for Western latitudes the reverse is true. Examination of the schematic diagrams below of the offset distance-amplitude curves will show that the distance for optimum detection shifts according as the test is closer or farther than the earthquake from the station; and as the station is near a minimum or maximum of the distance-amplitude relation.

Distance ranges for good Detection of Explosions



Earthquake closer to station than is Explosion

Distance ranges for good Detection of Explosions



Explosion closer to station than is Earthquake

Note in Figure 5 that the VLPE stations BOG and ZLP in South America just miss the regions of maximum detectability, whereas WWSSN stations in South America are in them. Good detectability is available at NUM and WRA in Australia. It must be noted, however, that detection of an explosion in the core shadow region of a masking earthquake with epicenter near the test site is probably not so desirable as detection in the PKP caustic region. Both signals in the core shadow zone are much weaker, are of lower frequency, and may even be difficult to detect in the presence of background noise for

events with magnitude m_b 5 or less. The signal observed in the core shadow zone will almost certainly be of less use for location, depth determination, and discrimination. Thus the loss of PKP detections due to weakness of the VELA net in South America and Antarctica would be more serious in a counter-evasion network than it might seem at first.

Two final points about Figure 5: the dotted line in Figure 2 was used for $\Delta < 10°$ instead of the solid line to avoid complexity in the Figures. Naturally, detection is much easier near the explosion and harder near the earthquake than is indicated in this and in subsequent figures. Secondly, this and subsequent figures have been calculated using the upper curve for $\Delta > 152°$. This is PKP_2 which arrives after PKIKP and with larger amplitude. However, the greater change of amplitude with distance near 152° for PKIKP shows that detection would be easier using PKIKP than using PKP_2 for $152° < \Delta < 153°$.

In Figure 6 we have changed the location of the earthquake to 45°N, 150°E, in the southern Kuril Islands. By so doing we have reversed the relative location of the explosion and earthquake with respect to teleseismic

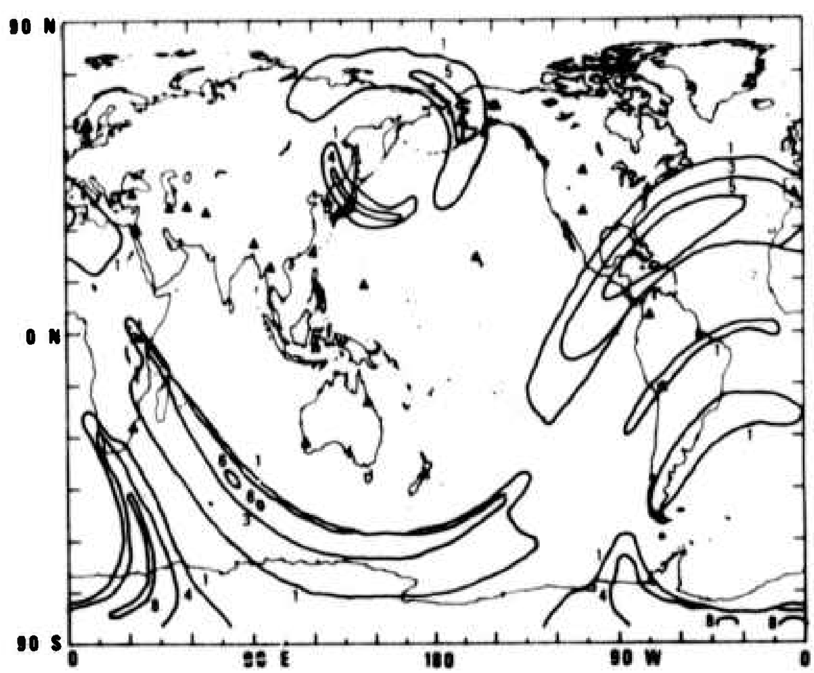


Figure 6. Positive differential logarithms of amplitudes received from an explosion located in Kamchatka at 52°N, 157.5°E and an equal magnitude earthquake located at 45°N, 150°E. Positive numbers indicate that the explosion signal is larger than the earthquake signal. Distance-amplitude relations are as described in Figure 2.

stations of interest. Where the earthquake was closer in the first instance, the explosion is closer now, and vice-versa. This changes the location of the maximum detectability regions in accordance with the discussions above.

It might occur that we know the epicenter of the earthquake, but we have no clear idea where, in the near vicinity of the earthquake, the explosion test site might be located. In this case inspection of a contour map of the absolute value of the $\log_{10}$ amplitude derivative with respect to distance will indicate those stations whose records will be useful to examine for evidence of hidden events near the earthquake. Of course, as we have seen in Figures 5 and 6, not all spots with large absolute values of the derivative will be suitable for any particular pair of events; in some cases the effect is to bury the explosion signal even deeper in the earthquake coda. However, for every large value in a contour map of the absolute value of the derivative of the logarithm of the amplitude with distance, there will be a substantial portion of the area around the earthquake for which detection of an explosion will be enhanced.

Figure 7 is such a log-derivative map. Note that because of the segmental linearization of the distance-amplitude curve used in the computer program the

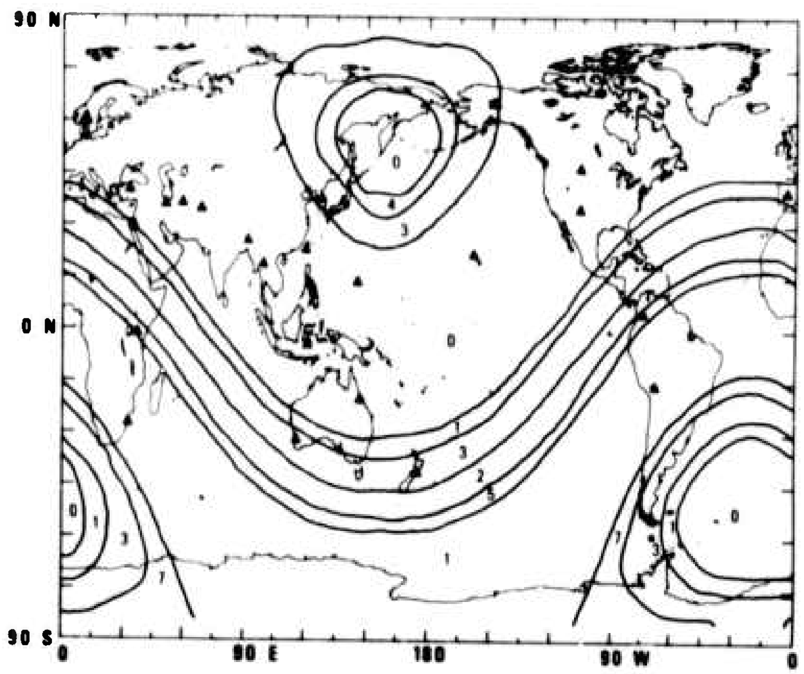


Figure 7. Absolute value of the derivative of the distance-amplitude relation as described in Figure 2. Amplitudes centered in Kamchatka at 52°N, 157.5°E. Units are tenths of a magnitude per five-degree differential.

transitions between levels of the derivative are very sharp. For this type of map we have therefore labeled the levels instead of the contours.

Comparison with Figures 5 and 6 shows that Figure 7 rather well predicts the regions of good detection, and in addition fills in some other areas which would be good detection areas if the earthquakes were to the northwest or southeast of the explosion. Again, stations BOG and NAI in Columbia and Africa are well favored, as would be stations in Southern Brazil, Argentina, Chile, and Antarctica.

Figures 8a and 8b are positive differential logarithm diagrams for events along the Kamchatka-Kuril Island chain somewhat closer to the explosion than was the case for Figures 5 and 6. We see that the magnitude differentials decline, as would be expected. Figure 8c is the average of Figures 5, 6, 8a, and 8b. It might be regarded as a map showing where to put stations for counterevasion of testing in a suggested test site on the Kamchatka Peninsula. If the seismicity were uniformly distributed in azimuth around Kamchatka, one would want this map to strongly resemble Figure 7. The discrepancies

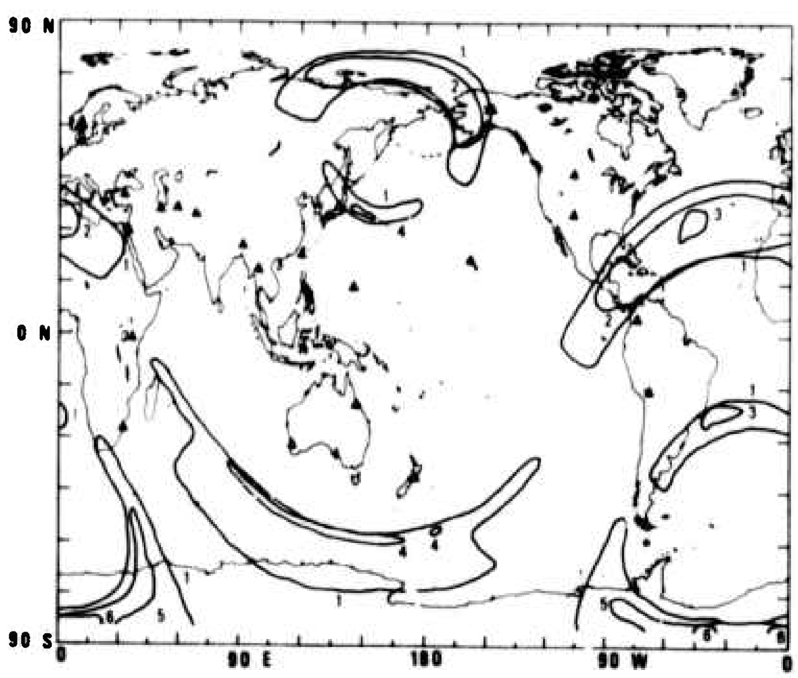


Figure 8a. Positive differential logarithms of amplitudes received from an explosion located in Kamchatka at 52°N, 157.5°E and an equal magnitude earthquake located at 48°N, 155°E. Positive numbers indicate that the explosion signal is larger than the earthquake signal. Distance-amplitude relations are as described in Figure 2.

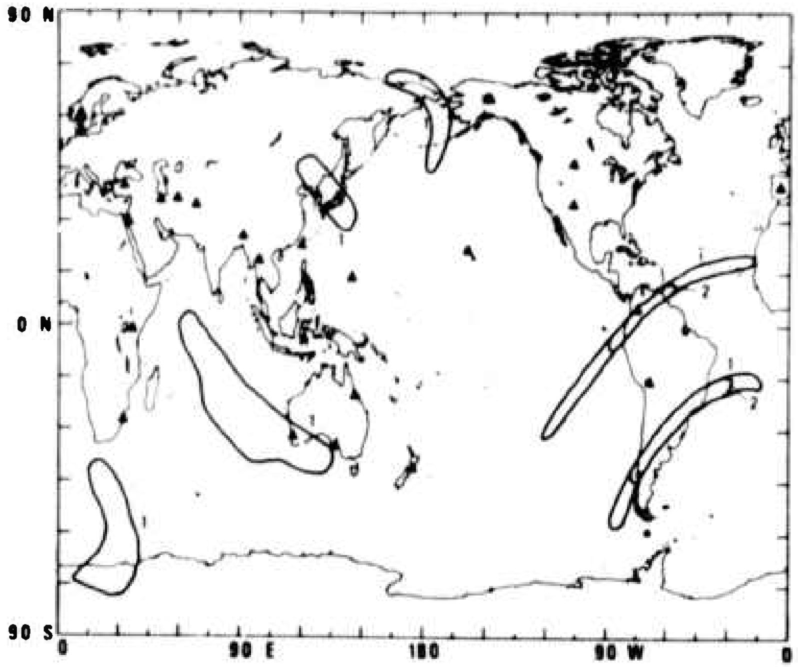


Figure 8b. Positive differential logarithms of amplitudes received from an explosion located in Kamchatka at 52°N, 157.5°E and an equal magnitude earthquake located at 53°N, 160°E. Positive numbers indicate that the explosion signal is larger than the earthquake signal. Distance-amplitude relations are as described in Figure 2.

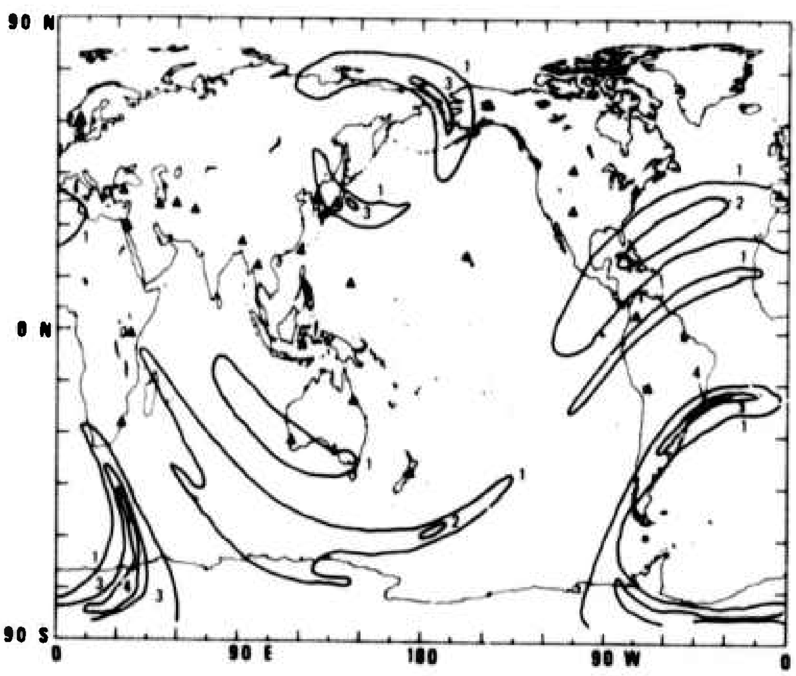


Figure 8c. Average of Figures 5, 6 8a, and 8b.

between Figures 7 and 8c are principally due, as mentioned above, to the fact that fewer earthquakes occur northwest and southeast of the chain than along the chain.

Figure 9 is similar to Figure 8c in that it gives the regions of enhanced detection of an explosion in Amchitka with respect to earthquakes along the Aleutian arc. We see that station SWZ in Africa would be good for detection together with the possibility of stations in Alaska and on the fringes of Antarctica.

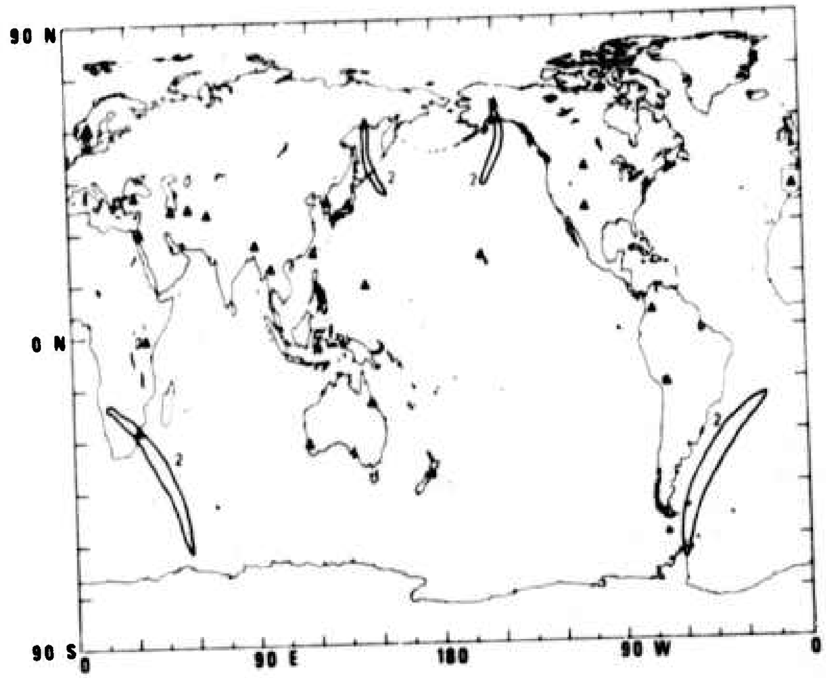


Figure 9. Average of positive magnitude differentials for an Aleutian explosion on Amchitka, 51°N, 179°E, with respect to an array of earthquakes spread out along the Aleutian arc.

Figure 10a shows that suitable counterevasion sites for a test at NTS with respect to an earthquake in Alaska include Brazil, Bolivia, Northern Chile, Australia, Africa, and, of course, Mexico, Canada, and the United States. Again for NTS, and for an earthquake in central America, Figure 10b shows that possible detection sites include Canada, Japan, Korea, the USSR,

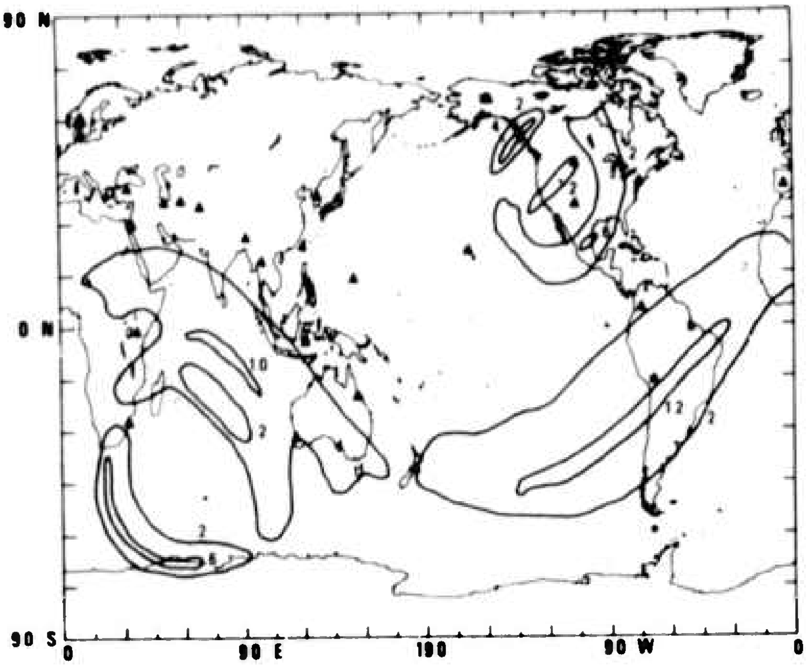


Figure 10a. Positive magnitude differentials of a NTS explosion, 37°N, 116°W with respect to an Alaskan earthquake, 58°N, 154°W. Distance-amplitude relation as in Figure 2 except that lower dashed line used for 103° < Δ < 113°.

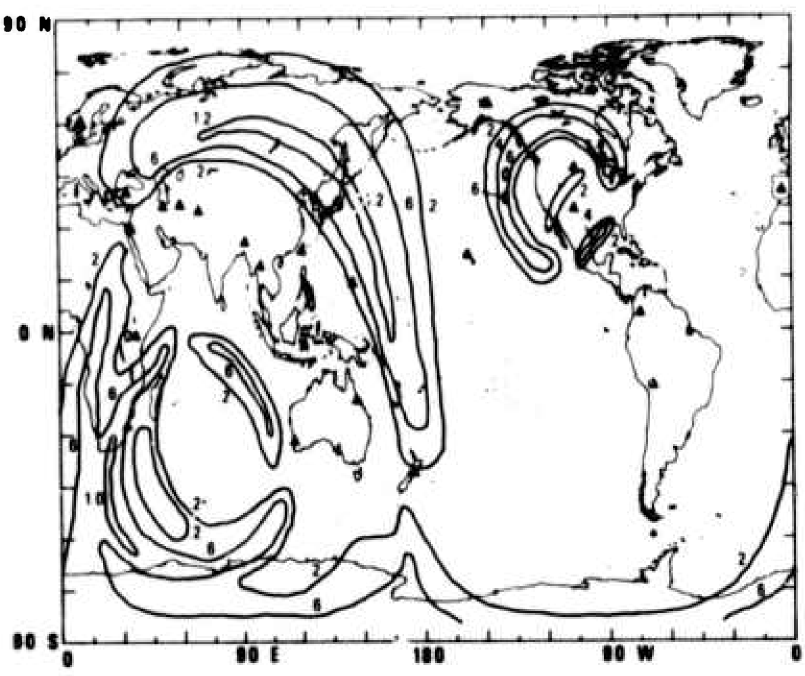


Figure 10b. Positive magnitude differentials of a NTS explosion, 37°N, 116°W with respect to a central American earthquake, 15°N, 90°W. Distance-amplitude relation as in Figure 2 except that lower dashed line used for 103° < Δ < 113°.

and Southern Africa. Obviously it is difficult to hide an NTS test in an earthquake. Note that for this figure and for others to follow in which the earthquake is more than 20° from the explosion, we have used the dashed line for $103° < \Delta < 113°$ in Figure 1 instead of the solid line. This line represents the PP amplitude shifted down by .6 m_b to account for the system response of an LRSM system at T = 1.6 sec (typical for PP as compared to 1 Hz P wave). For nearby earthquakes the evader will hide in the early P coda, but for teleseismic events the maximum amplitude of the total coda may be of greater interest. The only satisfactory existing way to evaluate evasion opportunities due to this more complex coda shape is with programs developed by Blandford and Husted (1973).

Figure 10c can be used to discuss the situation of counterevasion with respect to hiding a test at NTS in the coda of a nearby earthquake. The display of the absolute value of the derivative seems most appropriate here since NTS is, in fact, surrounded fairly uniformly by seismicity. Good detecting stations are found in Southern Africa and in Southwest Australia, and would also be found in Southern Argentina and Chile, the fringe of Antarctica, and in the United States and Canada.

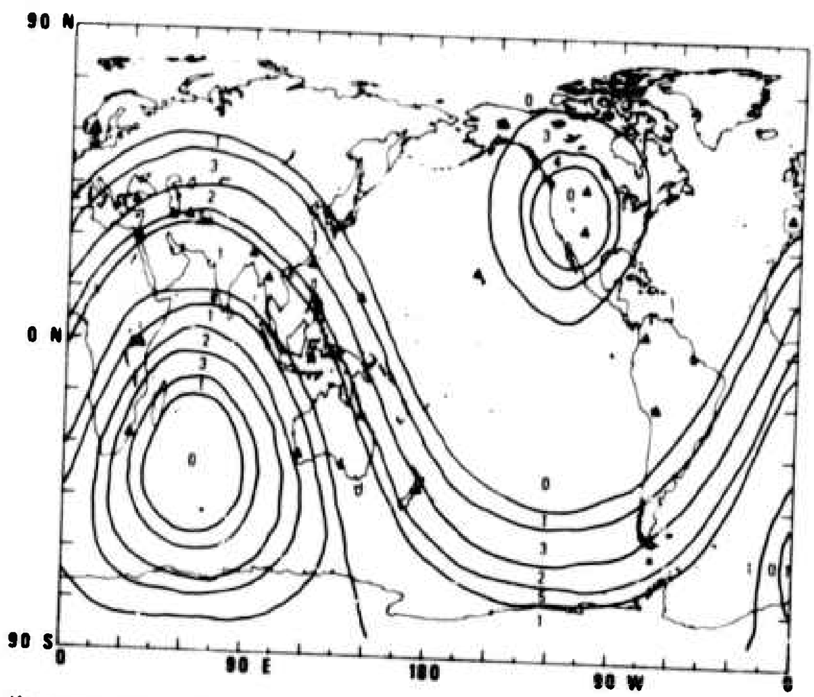


Figure 10c. Absolute value of the derivative of the distance-amplitude relations as described in Figure 2. Amplitudes centered at NTS at 37°N, 116°W. Units are tenths of a magnitude unit per five-degree differential. Distance-amplitude is as described in Figure 2.

In Figure 11a we see that suitable counterevasion sites for a test near the Caspian Sea with respect to an earthquake in the Persian Gulf include several sites in the United States, including LASA. The best PKP detection region touches WEL in New Zealand and detection is also highly enhanced at KBL in Afghanistan, and in Northeastern Australia. In Figure 11b we present the absolute derivative contour map, which is suitable because the Caspian Sea test site is in a region of diffuse seismicity. Here we see good PKP detection possibilities in New Zealand, as found above. Further, the core shadow zone cuts a great swath across North and South America, and across Australia. Note that a fair portion of the caustic detection zone intersects Antarctica.

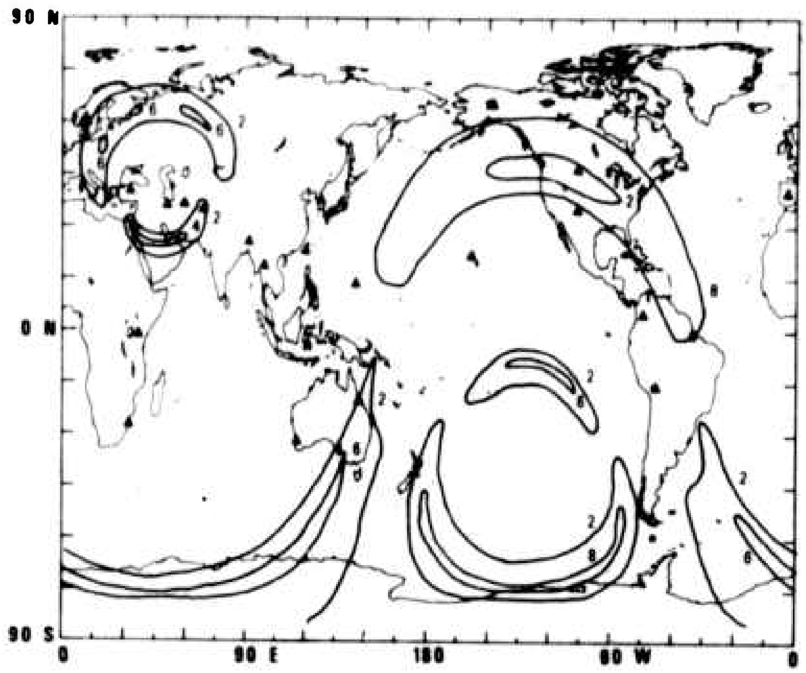


Figure 11a. Positive magnitude differentials of a Caspian Sea explosion, 43°N, 45°E, with respect to a Persian Gulf earthquake, 30°N, 48°E. Distance-amplitude relation is as described in Figure 2.

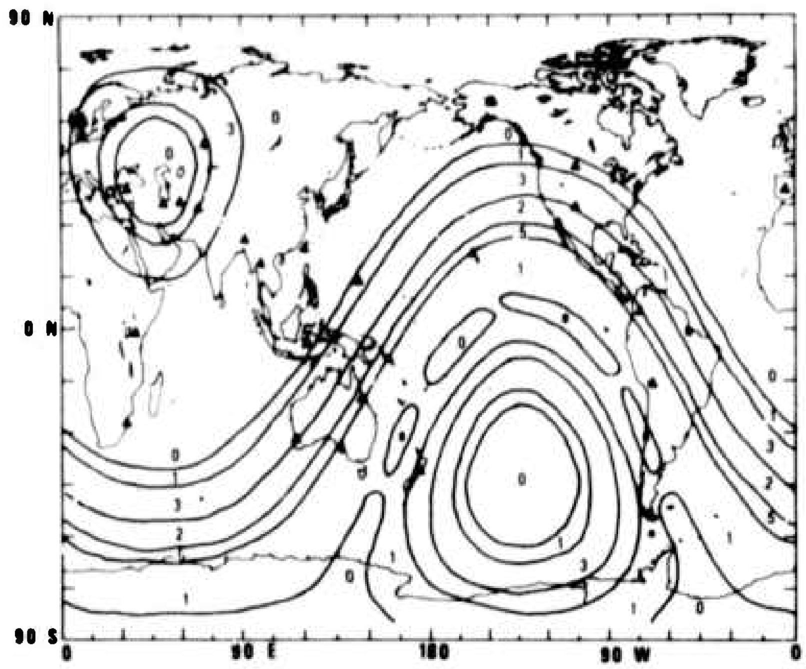


Figure 11b. Absolute value of the derivative of the distance-amplitude relation as described in Figure 2. Amplitudes centered at 43°N, 45°E near the Caspian Sea. Units are tenths of a magnitude unit per five-degree differential.

Finally, we consider the test site at Semipalatinsk. There is very little regional seismicity so we consider countermeasures with respect to earthquakes in the Hindu-Kush and the Philippine Islands.

Figure 12a shows that detections are easiest, in the presence of a Hindu Kush earthquake, in Antarctica with respect to the PKP caustic, and in the United States and Antarctica with respect to the core shadow zone. Close-in detections are also possible at KBL in Afghanistan, although some of this capability may be misleading and due to the flattening of the distance-amplitude curve used in the analysis near 0°, as indicated in Figure 1.

With respect to an earthquake in the Philippine Islands, Figure 12b shows that there are substantial detection possibilities in the United States, and in Spain and Africa. The maximum PKP detection capability is again found in Antarctica. Overall, detection of tests at Semipalatinsk should be quite easy.

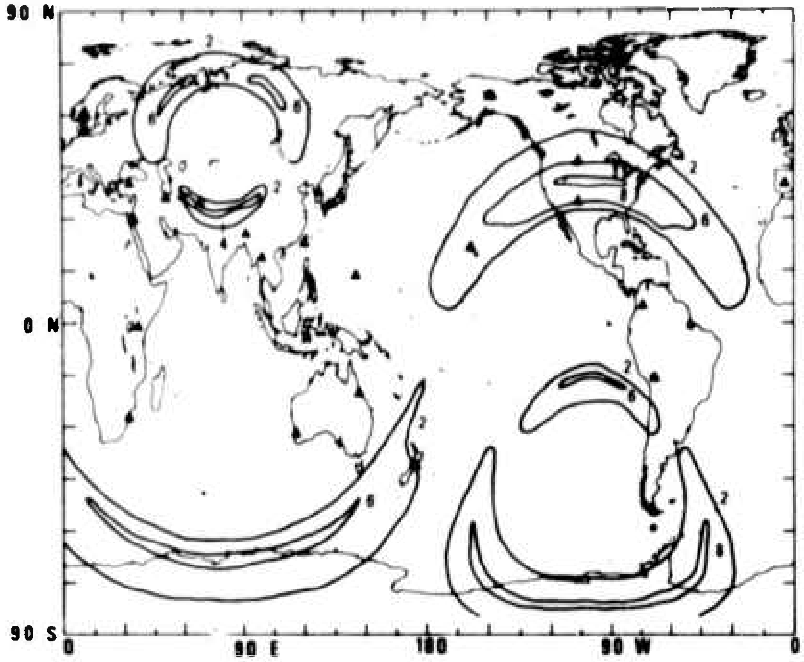


Figure 12a. Positive magnitude differentials of a Semipalatinsk explosion, 50°N, 78°E with respect to a Hindu-Kush earthquake, 38°N, 78°E. Distance-amplitude relation is as described in Figure 2.

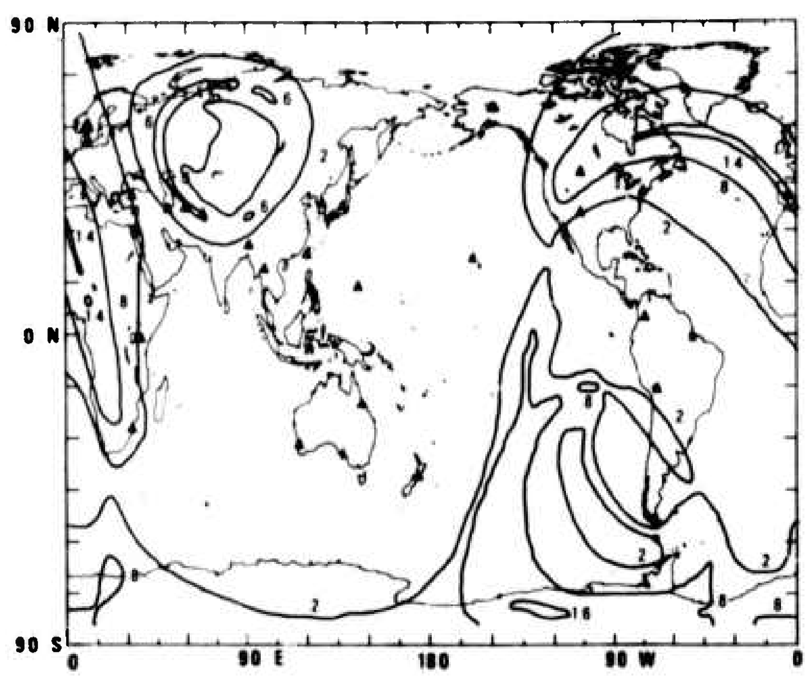


Figure 12b. Positive magnitude differentials of a Semipalatinsk explosion, 50°N, 78°E with respect to a Philippines earthquake, 15°N, 120°E. Distance-amplitude relation is as in Figure 2 except that dashed line is used for 103° < Δ < 113°.

POSSIBLE OPERATIONAL PROCEDURES AND SUGGESTIONS FOR FURTHER RESEARCH

From this study we conclude that a substantial reduction of the power of the HIE technique may be achieved by careful examination of records from selected stations world-wide. It seems clear that a very large number of stations, most of which would not be examined for any particular event, are required if this countermeasure is to work most efficiently. It would seem to be useful to install arcsinh amplifiers (Wu and Jarrold, 1974) between the paper records and the rest of the seismic system so that the records will remain on scale for the largest events.

A possible operational procedure to be followed in a test-ban situation would be as follows:

1. From the prompt reporting network, scan records from stations in the earthquake shadow zone especially carefully. Arrays in the prompt network could be analyzed by iterative beam-forming as discussed by Blandford et al. (1973).

2. If the earthquake is near a possible test site, scan any prompt reporting stations in the regions of high absolute distance-amplitude derivative.

3. Select the best four or five well-distributed non-prompt reporting stations in the high-derivative regions and order data for later routine inspection. Be sure to include at least two stations which recorded PKP, if possible.

4. If there are two or three test sites which are especially worrisome, those prompt and non-prompt reporting stations should be examined for which explosions at the test sites would be most easily detected.

Wu, F. T. and E. Jarrold, 1974, Arcsinh amplification/compression in seismic recording, Bull. Seism. Soc. Am., v. 64, p. 1591-1594.

Blandford, R. R., T. J. Cohen, and J. W. Woods, 1973, An iterative approximation to the mixed signal processor, SDAC-TR-73-7, Teledyne Geotech, Alexandria, Virginia. AD 002 277.

It seems clear that by comparison to the benefits they could bring to a counter-HIE program there are not enough WWSSN stations in Antarctica. Twelve visually recording stations spaced around the perimeter of the continent would constitute an impressive countermeasure. As of this writing, July 1975, there are nearly enough operational stations in Antarctica for effective use as a countermeasure but only three of them are WWSSN. The installation of a few historically occupied WWSSN sites would yield a highly effective counter-network.

To make confident use of this countermeasure, we need to assemble profiles of event signals as they are recorded in the shadow zone and the PKP caustic zone. Superpositions of events should help to show explicitly the effects discussed in this report. Such a study could be easily accomplished using LASA and LRSM data for the shadow zone; however, we have seen in this report how the PKP caustic from seismically active regions commonly lies in the Pacific and on Antarctica.

The HIE program discussed by Blandford and Husted (1973) should be extended to include the effects of PKP detection; in particular we should model the application of this countermeasure by assuming that stations are to be examined from within a few degrees of the most advantageous test sites on land. It seems clear that this will greatly reduce the number of opportunities per year to evade detection, even when earthquakes very close to the test site are used.

REFERENCES

Blandford, R. R. and D. Clark, 1975, Variability of seismic waveforms at LASA from small subregions of Kamchatka, SDAC-TR-75-12, Teledyne Geotech, Alexandria, Virginia.

Blandford, R. R. and E. I. Sweetser, 1975, Short-period earthquake coda shape as a function of geology and system response, SDAC-TR-75-10, Teledyne Geotech, Alexandria, Virginia.

Blandford, R. R., T. J. Cohen, and J. W. Woods, 1973, An iterative approximation to the mixed signal processor, SDAC-TR-73-7, Teledyne Geotech, Alexandria, Virginia.

Cohen, T. J., E. I. Sweetser, and T. J. Dutterer, 1972, P and PKP coda decay characteristics for earthquakes, Seismic Data Laboratory Report No. 301, Teledyne Geotech, Alexandria, Virginia.

Cohen, T. J. and E. I. Sweetser, 1973, False alarm probabilities for mixed events, SDAC-TR-73-8, Teledyne Geotech, Alexandria, Virginia.

Evernden, J., 1976, Study of seismological evasion, Part I, general discussion of various evasion schemes, Bull. Seis. Soc. Am., v. 66, p. 245-280.

Filson, J. R., 1973, On estimating the effect of Asian earthquake codas on the explosion detection capability of LASA, Technical Report 1973-29, Lincoln Laboratory, Massachusetts Institute of Technology.

Isherwood, W. F., 1970, Investigation of PKP seismic waves, Project PHV 6495, Stanford Research Institute, Menlo Park, California.

Jeppsson, I., 1975, Evasion by hiding in earthquake, FOA Rapport C 20042-T1, Forsvarets Forskningsanstalt, Stockholm, Sweden.

Lukasik, S., 1971, In Hearings on Status of current technology to identify seismic events as natural or man-made, before the Joint Committee on Atomic Energy of the Congress of the United States, October 1971. GPO No. 69-648.

REFERENCES (Continued)

Shumway, R. and R. R. Blandford, 1974, An examination of some new and classical short-period discriminants, SDAC-TR-74-10, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and R. R. Blandford, 1973, Seismic distance-amplitude relations for short-period P, P_{diff}, PP and compressional core phases for $\Delta > 90°$, SDAC-TR-73-9, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1973, Average P and PKP codas for earthquakes (103°-118°), SDAC-TR-73-10, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I., T. J. Cohen, and M. F. Tillman, 1973, Average P and PKP codas for earthquakes, Seismic Data Laboratory Report No. 305, Teledyne Geotech, Alexandria, Virginia.

Sweetser, E. I. and T. J. Cohen, 1974, Average P and PKP codas for earthquakes (118°-180°), SDAC-TR-74-19, Teledyne Geotech, Alexandria, Virginia.

Veith, K. F. and Clawson, G. E., 1972, Magnitude from short-period P-wave data, Bull. Seism. Soc. Am., v. 62, p. 435-452.

Wu, F. T. and E. Jarrold, 1974, Arcsinh amplification/compression in seismic recording, Bull. Seism. Soc. Am., v. 64, p. 1591-1594.